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Embedded energy and total greenhouse gas emissions in final consumptions within Thailand

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Abstract

In order to quantify the total Greenhouse Gas (GHG) emissions from different commodities, the contribution of emissions in all subprocess chains has to be considered. In embedded energy analysis, the higher order production processes are usually truncated due to a lack of data. To fill the truncated subprocesses up to infinite process chains, energy intensities and GHG emission factors of various final consumptions in the economy evaluated by the Input–Output Analysis (IOA) must be applied. The direct GHG emissions in final consumptions in Thailand are evaluated by imitating the approach in the energy sector of the revised 1996 Intergovernmental Panel on Climate Change (IPCC) guidelines for national GHG inventories. The indirect energy and indirect emissions are evaluated by using the 1998 Input–Output (I–O) table. Results are presented of emissions in the main process, indirect processes, and on each subprocess chain order. The trend of energy intensity and emission factors of all final consumptions for 1995, 1998, 2001 and 2006 are also presented. Results show that the highest energy intensive sector is the electricity sector where fossil fuel is primarily used, but the highest total GHG emitter is the cement industry where the major sources of the emissions are industrial processes and the combustion of fossil fuels. Implication of the emission

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factors on electricity generating technologies shows that various cleaner electricity generating technologies, including renewable energy technology, could help in global GHG mitigation.

Keywords: GHG emissions; Energy intensity; Input–output analysis; Full-energy-chains-analysis; Clean electricity generating technology

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Contents

1. Introduction

To increase the quality of life, per capita energy consumption is increasing and inducing higher exploitation of fossil fuels and larger amounts of Greenhouse Gases (GHGs) concentrating in the atmosphere. Thailand, as a member in Annex B countries in the Intergovernmental Panel on Climate Change (IPCC), reported national GHGs inventories in the first 'National GHGs Inventory of 1990', released in 1997 and updated to the 1994 inventory in 2000. It is reported that CO_2 emissions, the major GHG that is mainly emitted from energy activities, from energy sector in 1994 was 125.6 million tons [1].

Direct emission estimation is not sufficient for specifying the total GHG emissions in the economy, where the indirect emission is hidden. In order to sell an amount of material or service to final consumers, it needs various materials and services from other sectors in the economy (see Fig. 1). Within every single link of material or service supplied, GHGs are possibly released. In order to support the GHGs mitigation options among energy activities effectively, it is necessary to quantify the total emissions content in each commodity in terms of full energy chain analysis. In order to produce a final consumption, not only energy in the producing sector, but also indirect energy embedded in other inputs for the sector are required and the embedded energy emits GHG during conversions of energy in the whole energy chains.

There are two approaches available for full-energy-chains-analysis, i.e. Process Chain Analysis (PCA) and Input–Output Analysis (IOA). The PCA requires physical units of material inputs and needs tedious effort for input data from other processes, where the energy requirements of the main production processes and some important contributions from suppliers of inputs into the main processes are aggregated in details by auditing [2].

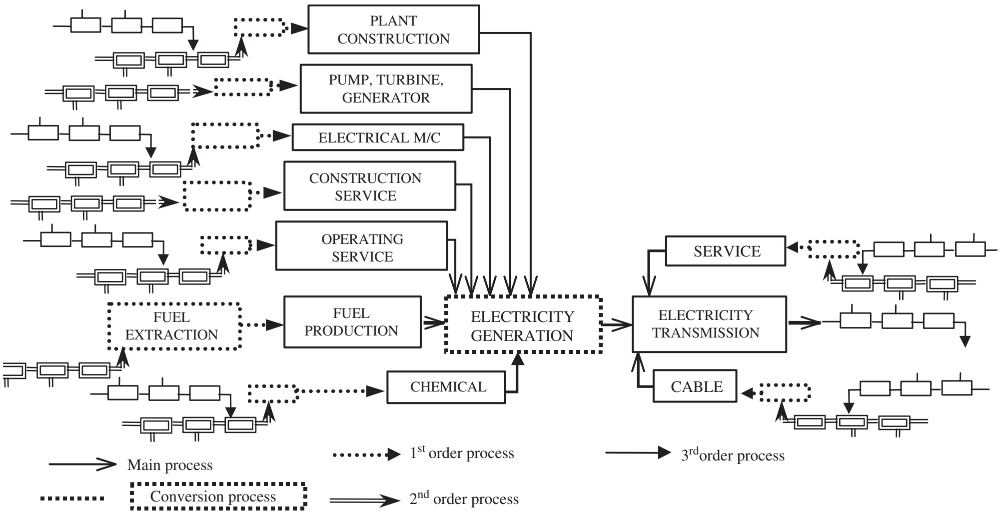


Fig. 1. Incorportion of commodities' emission factors for full-energy-chains analysis of an electricity generation technology.

Friedrich and Marheineke [3], and Lenzen and Dey [4] explained that PCA does not have a clear beginning, and a number of steps have been cut somewhere within the upstream link. On the other hand, requiring only cost breakdown, IOA can cope with material and non-material inputs [5,6]. It takes advantage in capturing all propagation of energy and GHGs from production chains up to infinite orders, and provides sufficient results for comparison among commodities, plus time and cost efficiency for data gathering and calculation tasks [7].

PCA is mostly applied in Thailand. It is accurate in the main process, but its analysis in the higher order production process is usually truncated due to lack of data [8]. The IOA is used to calculate energy intensities and GHG emission factors of various final consumptions in the economy to fill the truncated subprocesses up to infinite process chains by assigning an economic sector to represent all commodities produced from the same sector. Comparison of total GHG emissions among different energy technologies in terms of full-energy-chains analysis could be done by applying the results from IOA to a life-cycle analysis of considered systems. In addition, not only emissions from material but also services could be taken into account in the IOA.

In this article, IOA is applied to full-energy-chains analysis in the estimation of GHG emissions from energy activities in all producing chains, of final consumptions of economic sectors. The flows of materials, services and energies are traced back through infinite transactions within the economy, and GHG emissions embedded in the flows are quantified. Then the gap of missing embedded emissions in the higher order subprocess chains, that the PCA could never be completed due to lack of data, could be filled out by incorporating the commodity energy intensities and emission factors in the remaining subprocess chains.

The energy-related GHG emission including emissions from burning of fossil fuel, fugitive emissions, and emissions from industrial process are considered. The revised 1996 IPCC guidelines (IPCC) [9–11] are applied to sectoral derivation of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions. Emissions from the Thai economy

have been estimated based on the 1995 sectoral energy consumption and 1998 Input–Output (I–O) tables, provided by the National Economic and Social Development Board (NESDB) [12]. This study considers fossil fuels that are used as feedstock in some production processes, but there are no GHG emissions. Embedded emission in imported secondary energy is also taken into account.

2. Methodology

2.1. Input– Output analysis

In 1986 Wassily Loentief [13] introduced the theory of IOA and it was presented by Miller and Blair [14] in energy input–output analysis. It has been widely applied for derivation of energy intensity by Bullard and Herendeen [15], Wright [16] and Chapman [17]. Application of input–output techniques for derivation of full-energy-chain GHG emissions from power generation, have been presented in an advisory group meeting of the International Atomic Energy Agency (IAEA) held in Beijing, China in 1994 [3].

A particular economic sector requires various inputs starting from implementation, operation to decommissioning stages including services, energy and materials. Total emissions generated from all production of all purchased commodities and services are derived with Loentief's Inverse matrix $[\mathbf{I}-\mathbf{A}]^{-1}$. It is an integration of the direct effect and indirect effect of all subprocesses, until infinite subprocesses. Direct emissions are derived by the physical amount of each type of fossil energy that is directly combusted within the sector. The matrix of total energy content is

$$\mathbf{f} = [\mathbf{F}][\mathbf{I} - \mathbf{A}]^{-1} \tag{1}$$

A is a square n!n matrix representing the inter-industrial transaction of n industries within the economy. **I** is a unity matrix. The matrix **F** has a dimension of $k \times n$ where k is the number of fuel types. Each element of the sectoral energy consumption matrix (F_{ki}) is the direct consumption of fuel k in a physical unit by the monetary output of the economic sector i.

The energy intensity (EI) is the multiplication of the transpose of the vector of conversion factor [18] and the total energy content **f** i.e.

$$\mathrm{EI}^T = [\text{conversion factor}_{\mathrm{f}\times 1}]^T[\mathbf{f}_{f\times n}] \tag{2}$$

Each element of the energy intensity EI_i $(i = 1, \ldots, n)$ represents the energy intensity of sector i in the economy. Emission attributable to transactions outside national borders could also be assumed in the I–O model [19], but the assumption made is that there is no disparity between different products from the same sector. Imports of commodities, represented by the import matrix **M**, that are required by local industry, are introduced into the Eq. (1). Each element, M_{ij}, is the monetary amount of imports supplied from the foreign industry i to the domestic industry j per total monetary-domestic industry output of j. The total energy content including effect of import commodities to the economy is

$$\mathbf{f}^* = [\mathbf{F}][\mathbf{I} - [\mathbf{A} + \mathbf{M}]]^{-1} \tag{3}$$

The term $\mathbf{A}+\mathbf{M}$ represents a compound direct requirements matrix, and the term $[\mathbf{I}-[\mathbf{A}+\mathbf{M}]]^{-1}$ is a partially closed Loentief inverse [19].

Direct multiplier **I** yields the direct energy consumption. Integration of all indirect processes gives the sum of

$$[\mathbf{A}+\mathbf{M}]+[\mathbf{A}+\mathbf{M}]^2+[\mathbf{A}+\mathbf{M}]^3+\cdots+[\mathbf{A}+\mathbf{M}]^p+\cdots+[\mathbf{A}+\mathbf{M}]^\infty \tag{4}$$

where each term of $[\mathbf{A}+\mathbf{M}]^p$ represents the contribution of the process chain order $P+1$. Applying each element of **F** with the IPCC emission factors for estimation of CO_2 emission from combustion [9–11] yields a matrix of sectoral CO_2 emission, **B**, with

$$B_{ki} = F_{ki} \times \text{conversion factor}_k \times \text{carbon emission factor}_k \times \text{fraction of carbon oxidized}_k \times (44/12) \tag{5}$$

The carbon emission factor relies on the fuel type k. The fraction of carbon oxidation for coal, oil and gas of 0.98, 0.99 and 0.995, respectively [9–11]. A vector of total sectoral CO_2 emission factors that includes infinite propagation of production chains of domestic or import commodities incurring in any economic sector is

$$\mathbf{b} = [\mathbf{B}][\mathbf{I}-\mathbf{A}-\mathbf{M}]^{-1} \tag{6}$$

Since emission factors for CH_4 and N_2O rely on not only fuel type, but also activities [9–11], each economic sector is assumed to be equal in activities. A matrix of sectoral CH_4 or N_2O emissions, **B**, comprises of elements of

$$B_{ki} = F_{ki} \times \text{conversion factor}_{ki} \tag{7}$$

And the total CH_4 and N_2O emissions, from combustion activity is

$$\mathbf{b}CO_2 = \mathbf{d}CO_2[\mathbf{I}-\mathbf{A}-\mathbf{M}]^{-1} \tag{8}$$

$$\mathbf{b}_{\text{non}-CO_2} = \mathbf{d}_{\text{non}-CO_2}[\mathbf{I}-\mathbf{A}-\mathbf{M}]^{-1} \tag{9}$$

The IPCC's CH_4 emission factor and N_2O emission factor rely on fuel type and activity. The activity is located by the I–O sectors.

Generally, fuel is usually combusted in a sector, but in some particular processes a fuel requirements purpose is for feedstock beyond the combustion. Hence, the calculations of GHGs would be overestimated by using the matrix **F**. The overestimation of GHG emissions could be improved by introducing multiplier elements e_{ki} on every F_{ki} element.

$$F^*_{ki} = F_{ki} \cdot e_{ki} \tag{10}$$

The elements of matrix **F** are adjusted by Eq. (10), then each element of F_{ki} in Eq. (5) is substituted with F_{ki}. Where e_{ki} is 1 if fuel type k is combusted in sector i and e_{ki} is 0 if the fuel type k is used as feedstock in the sector i. The matrix **e** was recently introduced by Lenzen and Dey [4] and Lenzen [20] who constructed **e** in a vector, containing e_{ki} elements as 1 for any fuel that is used for combustion and as 0 for fuel used as feedstock in sector i. The element of the matrix **e** in this study was expanded to extend the function of them, not only of the fuel types, but also the process activities as described.

To avoid double counting, only primary energy should be taken into account in derivation of GHGs from domestic energies. However, the import of secondary energy is usually stepped over, but is more or less significant in terms of embedded GHG emission. This study also considers GHG embedded in imported energies in primary and secondary energies. Imported electricity is particularly considered, since there is no emission factor provided, but its GHG content is quite significant.

Direct GHG emissions from non-combustion activities were constructed as a vector i.e. $\mathbf{d}'$. The amount of fugitive emissions from domestic fossil fuel productions of solid, liquid and gaseous fuels have been evaluated [21]. Since research on local conditions and circumstances is not available, estimation of fugitive emissions by the global average method is applied. GHG emissions from industrial process are assumed to equal to the same amount as reported in 'the industrial process sector' [1].

Taking into account the propagation of non-combustion activities in all subprocess chains, the total non-combustion emission of each GHG is $\mathbf{d}'[\mathbf{I}-\mathbf{A}-\mathbf{M}]^{-1}$. Then the total CO_2 emission is

$$\mathbf{b}_{CO_2} = \mathrm{d}_{CO_2}[\mathbf{I}-\mathbf{A}-\mathbf{M}]^{-1} + \mathbf{d}'CO_2[\mathrm{I}-\mathrm{A}-\mathrm{M}]^{-1} \tag{11}$$

Similarly, the total of non-CO_2 gas, i.e. CH_4, N_2O, NO_x, CO, and NMVOC emissions are derived by

$$\mathbf{b}_{non-CO_2} = \mathbf{d}_{non-CO_2}[\mathbf{I}-\mathbf{A}-\mathbf{M}]^{-1} + \mathbf{d}'_{non-CO_2}[\mathbf{I}-\mathbf{A}-\mathbf{M}]^{-1} \tag{12}$$

Accounting for all GHGs, their Global Warming Potentials (GWPs) are applied. Since the GWPs of CO_2, CH_4, and N_2O in IPCC guidelines are 1, 21, and 310, respectively [9–11], the matrix of total GHG emissions, $\mathbf{b}^*$, is

$$\mathbf{b}^* = [\mathbf{b}_{CO_2} \quad \mathbf{b}CH_4 \quad \mathbf{b}N_2O]\begin{bmatrix} 1 \\ 21 \\ 310 \end{bmatrix} \tag{13}$$

2.2. Data preparation

Thailand I–O tables, available in four formats, i.e. 16×16, 26×26, 58×58, and 180×180 sectors, are published by the NESDB. In order to assign each sector and represent an average commodity produced from its own sector most efficiently, the 180×180 I–O table is selected for this analysis. The NESDB also provides recent disaggregated data for construction of the matrix **F** in 1995, in accordance with the 1995 I–O table [22]. Though the Department of Alternative Energy Development and Efficiency (DEDE) [18] publishes an annual report on energy consumption, higher disaggregation in economic sectors is insufficient.

The 1995 I–O table is tailor-made for a structural matrix. Each element of the provided 'new purchasing price' is the sum of the 'wholesale trade margin' plus the 'retailed trade margin', the 'transportation' and the 'import'. Prior calculations have to be made for finding the element of the 'domestic purchase' by subtracting the 'wholesale trade margin' with the 'retailed trade margin', the 'transportation' and the 'import'. Thereafter, the 'import' element is further constructed for the 'import' structural matrix. The capital structure is not considered in this study, since the elements of 'capital demand' are not internally provided in the input–output table.

Since there is no disparity of energy prices among economic sectors in the Thai economy, energy prices vary geographically, rather than by consumer type. Consequently, hybrid units, a hybrid of monetary and physical units in the I–O structure, as suggested by Miller and Blair [14], Wright [16], and Chapman [17] are not applied, and only the monetary unit in the intra-industrial flows is used in this study.

2.3. Applications of emission factors in comparative assessment of power generating technologies

Total energy content or total GHG emissions, from the lifecycle of a particular system or technology, could be covered to the whole infinite energy chains by incorporating energy intensities, or emission factors of final consumptions Fig. 1 presents the use of energy intensities or emission factors of final consumptions as the embedded energy or embedded GHG emissions in various inputs, in the main process of electricity generation technology.

The direct emission from each plant is derived by using physical units of energy consumption in the main process, and GHG emission factors of the IPCC [9–11].This stage requires physical units of all GHGs emitted, and energy input and output from the system. A list of materials and services purchased from the plant's lifetime, i.e. investment, annual energy consumption, and operation and maintenance is required. All physical amounts of energy used during the plant's lifetime will be classified, and they are evaluated for the related GHG emissions.

Indirect GHG emissions are derived from purchased materials and services from the economy for construction, conversion, and distribution stages commodities' emission factor, EF_i, of material or service i is performed by IOA, where the whole sub-process chains could be taken into account. Each part of the construction cost break down attributed to purchasing of materials or services from a particular economic sector, is responsible for the sector's energy intensity and GHG emissions. All of these cost categories are assigned to their appropriate economic sectors, accounting for their second to infinite energy chain, i.e. all indirect processes. The indirect effect is derived by

$$EF_{indirect}(gCO_{2\,equiv}/kWh)$$
$$\frac{\sum_{i=1}^{179}[EF_i(g\,CO_2\text{ equiv/million Bhat})\times\text{lifetime input requirement for sector } i\text{ (million Bhat)}]}{\text{lifetime electricity produced (kWh)}} \tag{14}$$

A power plant's emission factor is the life-cycle GHG emissions, directly and indirectly, per life-cycle of electricity produced. The net produced electricity is identified as the average energy per annum;

$$\text{Net energy (kWh/year)}\,\frac{\text{net energy output from life cycle}}{\text{lifetime of the powerplant}} \tag{15}$$

Five technologies are analyzed in terms of full-energy-chains, energy intensity and GHG emission factors, in order to represent possible power generation technologies that could be committed in Thailand. The five power generation technologies are (i) the GTCC case: a set of gas turbine and Gas Turbine Combined-Cycle plants [23], (ii) the fuel oil case: a fuel oil thermal power plant [24], (iii) the biomass case: a rice-husk power plant [25], (iv) the minihydro case: a run-of-river hydro-electric plant [26], (v) the PV case: a photo voltaic plant [27].

These power technologies are planned to be installed in 2006. PCA boundary relies on the availability of data for the process chain to be extended. Decommissioning is not taken into account. These cases are under different project stages including construction, commissioning, operating, and feasibility study stages.

The operating materials such as limestone, chemicals, fuels, and water are assumed to be re-purchased annually. The plants' lifetimes are assumed to be 50 years for the minihydro and 25 years for the GTCC. Renewal of equipment for maintenance relies on its lifetime, and the construction materials and related services lasting until the end of the plants' life time.

3. Results and discussions

3.1. Energy intensities and GHG emission factors

Energy intensities and GHG emission factors of final consumptions in 1998 are presented in Table 1. Final consumption of electricity is the highest in energy intensity, followed by cement, ocean transport, animal feed, iron and steel, ice, and basic industrial chemicals, respectively. However, the GHG emission factor is not the function of the energy intensity, since the amount of GHG emissions rely on the amount of fuel, fuel types, combustion, fugitive emissions, and upstream production process of commodities.

Cement is the highest GHG emitting commodity, followed by electricity, ocean transport, limestone, basic industrial chemicals, and iron and steel. Energy intensity in limestone is little, but its GHG emission factor is very high due to high direct emission in its industrial process (see Fig. 2). The energy intensity of the cement sector is the second highest, but its emission factor is the highest in the economy due to high direct emissions in combustion and also high direct emissions in industrial process. The energy intensity of the animal feed sector is high, but its emission factor is small. Fig. 2 also implies that it is important to take into account activities other than combustion, and neglecting subprocess chains would probably yield significant truncation errors.

Considering only the direct combustion process, would find very small GHG emissions in final consumptions of iron and steel, non-metallic products, concrete and cement products, and ice, but their GHG emission factors are very high in terms of full-energy-chains analysis. The other major contributors are emissions related to fugitive emissions, and emissions in some particular industrial process, such as cement production or limestone production, indirect emissions in higher order subprocess chains related to combustion activity. In ice production, although their is no emission in the main combustion process, 99.9% of GHG emission in the ice comes from combustion activity, and 84.4% is incurred in the second process chain which is mostly embedded in electricity that the ice production demands. 78% of emissions in concrete and cement products and 69.21% in non-metallic products is come from indirect emissions in the first subprocess chains. In iron and steel, the majority belongs to indirect subprocess chains related to combustion. Embedded emissions of 29.1% are embedded in the first subprocess chain, and 19.8% are embedded in the second process chain.

Fuel mix changes in the electricity sector indirectly affects energy intensities and GHG emission factors in all other sectors in the economy. The 1995 I–O table is applied for 1995 IOA, but 1998 I–O table is applied for 1998, 2001 and 2006 IOA. Four combinations of fuel mix in the power sector in 1995, 1998, 2001, and 2006 are shown in Fig. 3.

The trend of energy intensities and GHG emission factors of 180 final consumptions in 1995, 1998, 2001, and 2006 are also presented in Table 1. The energy intensities of most final consumptions in the economy have been decreasing from 1995, 1998 to 2001. Their

GHG emission factors also turn down. While the trend of the energy intensities from 2001 to 2006 has been increasing, the trend of GHG emission factors is decreasing due to lower portions of fuel oil and diesel, but higher portions of natural gas and renewable energy in the electricity sector. The trends of energy intensities and emission factors of most final consumptions are similar to the electricity sector. The fuel mix in the electricity sector affects most sectors in the economy that highly rely on electricity consumption. Some distinctive effects are incurred in other sectors that mainly require electricity such as ice production and some service sectors. Some sectors, that their trend of energy intensities and GHG emission factors are different from the electricity sector, mostly consume fuel for transportations.

The commodities' GHG emission factors derived by IOA, as presented in Table 1, could be applied to fulfill the truncated links in the PCA problem. An application of combining the IOA emission factors to the PCA is presented on the case of comparative assessment of electricity generation technologies.

3.2. *Comparative assessment of power generation technologies*

Energy intensities and GHG emission factors in terms of full energy chains analysis on the life-cycle of five case studies are presented for comparative assessment using IOA emission factors. GHG emission embedded in various inputs and embedded in subprocess chains are also presented in Table 2. Embedded emissions are also presented. Indirect energy and indirect GHG emissions are derived by GHG emission factors from IOA and cost breakdown.

It is seen that total cost, total GHG emission factors, and energy intensity of fuel oil electricity is higher than other electricity generation technologies, except the PV case. The PV case is not economically feasible for the GHG mitigation option for Thailand.

Although the total cost is higher in the GTCC case, it is a better option than the fuel oil plant, in terms of energy intensity and total GHG emissions. Among renewable resources in Thailand, biomass and minihydro are very promising. The biomass case presents the lowest emission factor, but its energy intensity and life-cycle cost are slightly higher than that of the minihydro. Energy intensities and GHG emissions in the biomass case and in the minihydro case are 10 times less than the GTCC case, but only 30–40% higher in their total costs.

In the GTCC case, about 85% of the indirect emissions is embedded in the first subprocess chain. The highest source of indirect energy and emission is the purchasing of natural gas. The contribution of indirect effects from purchasing natural gas, comes from not only emissions in the conversion of natural gas, but also indirect emissions in the fuel chains of natural gas production. The indirect emissions come mostly from combustion in petroleum production process, which is the second process of natural gas, the third process chain of the GTCC system. Engine and turbines, and water supply are responsible for 6 and 3%, respectively, of total emissions.

In the fuel oil case, about 44% of the indirect emissions are embedded in limestone that is the first subprocess of the system. Petroleum refinery is responsible for 40%. Special industrial machinery, and engines and turbines are responsible for 6.6 and 3.3%, respectively.

In renewable energy technologies, only indirect effects are absolutely responsible for the plants' energy intensities and emission factors. The life cycle costs and energy intensity of

Table 1
Trends of energy intensity and GHG emission factors

		Energy intensity (TJ/million Baht)					GHG emission factors (ton $CO_{2\ equiv}$/million Baht)				
		1998	1995	1998	2001	2006	1998	1995	1998	2001	2006
001	Paddy	0.151	⬩	◆	⬩	◆	11.22	◆	◆	⬩	⬩
002	Maize	0.244	◆	⬩	⬩	◆	17.92	◆	◆	⬩	⬩
003	Other cereals	0.243	⬩	◆	⬩	◆	17.30	⬩	◆	⬩	◆
004	Cassava	0.194	⬩	◆	⬩	◆	14.10	⬩	◆	⬩	◆
005	Other root crops	0.173	⬩	◆	⬩	◆	12.10	⬩	◆	⬩	◆
006	Beans and nuts	0.268	⬩	◆	⬩	◆	19.43	⬩	◆	⬩	◆
007	Vegetables	0.199	◆	⬩	⬩	◆	14.25	◆	◆	⬩	⬩
008	Fruits	0.151	◆	⬩	⬩	◆	10.87	◆	◆	⬩	⬩
009	Sugarcane	0.274	⬩	◆	⬩	◆	20.17	⬩	◆	⬩	◆
010	Coconut	0.057	◆	⬩	⬩	◆	4.20	◆	◆	⬩	⬩
011	Oil palm	0.253	◆	⬩	⬩	◆	19.43	◆	◆	⬩	⬩
012	Kenaf and jute	0.195	⬩	◆	⬩	◆	13.86	⬩	◆	⬩	◆
013	Crops for textile and matting	0.250	◆	⬩	⬩	◆	18.90	◆	◆	⬩	⬩
014	Tobacco	0.272	◆	⬩	⬩	◆	19.56	◆	◆	⬩	⬩
015	Coffee and tea	0.170	◆	⬩	⬩	◆	12.15	◆	◆	⬩	⬩
016	Rubber	0.128	◆	⬩	⬩	◆	9.69	◆	◆	⬩	⬩
017	Other agricultural products	0.183	◆	⬩	⬩	◆	12.30	◆	◆	⬩	⬩
018	Cattle and buffalo	0.362	⬩	◆	⬩	◆	8.91	⬩	◆	⬩	◆
019	Swine	1.048	◆	⬩	⬩	◆	24.99	◆	◆	⬩	⬩
020	Other livestock	0.384	◆	⬩	⬩	◆	8.70	◆	◆	⬩	⬩
021	Poultry	1.133	◆	⬩	⬩	◆	22.93	◆	◆	⬩	⬩
022	Poultry products	1.089	◆	⬩	⬩	◆	27.48	◆	◆	⬩	⬩
023	Silk worm	0.125	◆	⬩	⬩	◆	8.55	◆	◆	⬩	⬩
024	Agricultural services	0.771	⬩	◆	⬩	◆	55.36	◆	◆	⬩	⬩

025	Logging	0.123	◆	♦	♦	◆	8.16	◆	◆	♦	♦
026	Charcoal and firewood	0.063	◆	♦	♦	◆	3.76	◆	◆	♦	♦
027	Other forestry products	0.091	◆	♦	♦	◆	6.31	◆	◆	♦	♦
028	Ocean and coastal fishing	1.088	◆	♦	♦	◆	68.90	◆	◆	♦	♦
029	Inland fishing	0.591	♦	◆	♦	◆	26.51	♦	◆	♦	◆
030	Coal and lignite	0.561	♦	◆	♦	◆	40.19	♦	◆	♦	◆
031	Petroleum and natural gas	0.482	◆	♦	♦	◆	33.71	◆	◆	♦	♦
032	Iron ore	0.387	◆	♦	♦	◆	22.52	◆	◆	♦	♦
033	Tin ore	1.004	◆	♦	♦	◆	74.81	◆	◆	♦	♦
034	Tungsten ore	0.845	♦	◆	♦	◆	42.85	♦	◆	♦	◆
035	Other non-ferrous metal ore	0.282	◆	♦	♦	◆	19.92	◆	◆	♦	♦
036	Fluorite	0.726	◆	♦	♦	◆	49.89	◆	◆	♦	♦
037	Chemical fertilizer minerals	0.258	♦	◆	♦	◆	17.97	◆	◆	♦	♦
038	Salt evaporation	0.150	♦	◆	♦	◆	10.52	♦	v◆	♦	◆
039	Limestone	0.184	◆	♦	♦	◆	191.90	◆	◆	♦	♦
040	Stone quarrying	0.494	◆	♦	♦	◆	32.55	◆	◆	♦	♦
041	Other mining and quarrying	0.378	♦	◆	♦	◆	25.49	♦	◆	♦	◆
042	Slaughtering	0.758	◆	♦	♦	◆	19.17	◆	◆	♦	♦
043	Canning preserving of meat	0.618	◆	♦	♦	◆	25.55	◆	◆	♦	♦
044	Dairy products	0.604	◆	♦	♦	◆	35.36	◆	◆	♦	♦
045	Canning of fruits and vegetables	0.464	◆	♦	♦	◆	29.72	◆	◆	♦	♦
046	Canning preserving of fish	0.754	♦	◆	♦	◆	48.04	♦	◆	♦	◆
047	Coconut and palm oil	0.537	♦	◆	♦	◆	36.55	♦	◆	♦	◆
048	Other vegetable animal oils	0.638	◆	♦	♦	◆	42.75	◆	◆	♦	♦
049	Rice milling	0.672	◆	♦	♦	◆	12.55	◆	◆	♦	♦
050	Tapioca milling	0.434	♦	◆	♦	◆	27.36	◆	◆	♦	♦

Table 1 (*continued*)

		Energy intensity (TJ/million Baht)					GHG emission factors (ton $CO_{2\ equiv}$/million Baht)				
		1998	1995	1998	2001	2006	1998	1995	1998	2001	2006
051	Drying and grinding of maize	0.246	♦	◆	♦	◆	16.72	◆	◆	♦	♦
052	Flour and other grain milling	0.436	♦	◆	♦	◆	20.86	◆	◆	♦	♦
053	Bakery products	0.453	♦	◆	♦	◆	25.42	◆	◆	♦	♦
054	Noodles and similar products	0.531	◆	♦	♦	◆	27.76	◆	◆	♦	♦
055	Sugar	0.598	♦	◆	♦	◆	25.23	◆	◆	♦	♦
056	Confectionery	0.539	◆	♦	♦	◆	29.59	◆	◆	♦	♦
057	Ice	1.975	◆	♦	♦	◆	103.06	◆	◆	♦	♦
058	Monosodium glutamate	0.692	◆	♦	♦	◆	46.21	◆	◆	♦	♦
059	Coffee and tea processing	0.288	♦	◆	♦	◆	18.67	♦	◆	♦	◆
060	Other food products	0.460	◆	♦	♦	◆	26.88	◆	◆	♦	♦
061	Animal feed	2.624	◆	♦	♦	◆	35.78	◆	◆	♦	♦
062	Distilling blending spirits	0.376	◆	♦	♦	◆	25.32	◆	◆	♦	♦
063	Breweries	0.273	◆	♦	♦	◆	18.17	◆	◆	♦	♦
064	Soft drinks	0.422	◆	♦	♦	◆	26.64	◆	◆	♦	♦
065	Tobacco processing	0.944	◆	♦	♦	◆	65.54	◆	◆	♦	♦
066	Tobacco products	0.191	◆	♦	♦	◆	12.27	◆	◆	♦	♦
067	Spinning	0.783	◆	♦	♦	◆	47.92	◆	◆	♦	♦
068	Weaving	0.911	♦	◆	♦	◆	56.95	◆	◆	♦	♦
069	Textile bleaching and finishing	1.448	◆	♦	♦	◆	105.24	◆	◆	♦	♦
070	Made-up textile goods	0.791	♦	◆	♦	◆	52.23	◆	◆	♦	♦
071	Knitting	0.628	♦	◆	♦	◆	39.35	◆	◆	♦	♦
072	Wearing apparels except footware	0.614	♦	◆	♦	◆	37.92	◆	◆	♦	♦
073	Carpets and rugs	0.501	◆	♦	♦	◆	31.34	◆	◆	♦	♦

074	Cordage rope and twine products	0.534	♦	◆	♦	◆	38.06	♦	◆	♦	◆
075	Tanneries leather finishing	0.945	◆	♦	◆	♦	52.44	◆	◆	♦	♦
076	Leather products	0.464	◆	♦	♦	◆	30.05	◆	◆	♦	♦
077	Footwear except rubber	0.448	◆	♦	♦	◆	28.36	◆	◆	♦	♦
078	Saws mills	0.486	♦	◆	♦	◆	30.77	♦	◆	♦	◆
079	Wood and cork products	0.414	◆	♦	♦	◆	25.10	◆	◆	♦	♦
080	Furniture and fixtures wood	0.388	◆	♦	♦	◆	23.90	◆	◆	♦	♦
081	Pulp paper and paperboard	1.197	◆	♦	♦	◆	59.70	◆	◆	♦	♦
082	Paper products	1.000	◆	♦	♦	◆	59.95	◆	◆	♦	♦
083	Printing and publishing	0.640	◆	♦	♦	◆	35.91	◆	◆	♦	♦
084	Basic industrial chemicals	1.920	◆	♦	♦	◆	155.23	◆	◆	♦	♦
085	Fertilizer and pesticides	0.805	◆	♦	♦	◆	64.72	◆	◆	♦	♦
086	Synthetic resins and plastics	0.929	◆	♦	♦	◆	61.00	◆	◆	♦	♦
087	Paints varnishes and lacquers	0.730	◆	♦	♦	◆	53.29	◆	◆	♦	♦
088	Drugs and medicines	0.759	◆	♦	♦	◆	53.25	◆	◆	♦	♦
089	Soap and cleaning preparations	0.783	◆	♦	♦	◆	55.35	◆	◆	♦	♦
090	Cosmetics	0.710	♦	◆	♦	◆	47.48	◆	◆	♦	♦
091	Matches	0.528	◆	♦	♦	◆	35.34	◆	◆	♦	♦
092	Other chemical products	1.059	◆	♦	♦	◆	78.00	◆	◆	♦	♦
093	Petroleum refineries	0.360	◆	♦	♦	◆	25.21	◆	◆	♦	♦
094	Other petroleum products	0.777	◆	♦	♦	◆	58.13	◆	◆	♦	♦
095	Rubber sheets and block rubber	0.279	◆	♦	♦	◆	14.48	◆	◆	♦	♦
096	Tyres and tubes	0.752	◆	♦	♦	◆	49.02	◆	◆	♦	♦
097	Other rubber products	0.569	◆	♦	♦	◆	36.36	◆	◆	♦	♦
098	Plastic wares	0.827	♦	◆	♦	◆	52.38	◆	◆	♦	♦

Table 1 (*continued*)

		Energy intensity (TJ/million Baht)					GHG emission factors (ton $CO_{2\ equiv}$/million Baht)				
		1998	1995	1998	2001	2006	1998	1995	1998	2001	2006
099	Caramic and earthen wares	1.363	◆	◆	◆	◆	81.25	◆	◆	◆	◆
100	Glass and glass products	1.460	◆	◆	◆	◆	105.30	◆	◆	◆	◆
101	Structural clay products	1.370	◆	◆	◆	◆	79.86	◆	◆	◆	◆
102	Cement	2.637	◆	◆	◆	◆	424.56	◆	◆	◆	◆
103	Concrete and cement products	0.937	◆	◆	◆	◆	116.55	◆	◆	◆	◆
104	Other non-metallic products	1.038	◆	◆	◆	◆	117.31	◆	◆	◆	◆
105	Iron and steel	2.016	◆	◆	◆	◆	129.82	◆	◆	◆	◆
106	Secondary steel products	1.100	◆	◆	◆	◆	68.67	◆	◆	◆	◆
107	Non-ferrous metal	0.800	◆	◆	◆	◆	54.44	◆	◆	◆	◆
108	Cutlery and hand tools	0.532	◆	◆	◆	◆	34.02	◆	◆	◆	◆
109	Furniture and fixtures metal	0.659	◆	◆	◆	◆	41.00	◆	◆	◆	◆
110	Structural metal products	0.590	◆	◆	◆	◆	37.70	◆	◆	◆	◆
111	Other fabricated metal products	0.670	◆	◆	◆	◆	42.61	◆	◆	◆	◆
112	Engines and turbines	0.725	◆	◆	◆	◆	49.76	◆	◆	◆	◆
113	Agricultural machinery	0.568	◆	◆	◆	◆	36.75	◆	◆	◆	◆
114	Wood and metal working machinery	0.480	◆	◆	◆	◆	33.04	◆	◆	◆	◆
115	Special industrial machinery	0.640	◆	◆	◆	◆	43.18	◆	◆	◆	◆
116	Office and household machinery	0.302	◆	◆	◆	◆	19.30	◆	◆	◆	◆
117	Electrical industrial machinery	0.417	◆	◆	◆	◆	26.25	◆	◆	◆	◆
118	Radio and television	0.424	◆	◆	◆	◆	27.24	◆	◆	◆	◆
119	Household electrical appliances	0.680	◆	◆	◆	◆	43.75	◆	◆	◆	◆

120	Insulated Wire and Cable	0.548	◆	⬥	⬥	◆	35.49	◆	◆	⬥	⬥
121	Electric accumulator and battery	0.705	◆	⬥	⬥	◆	49.55	◆	◆	⬥	⬥
122	Other electrical aparatuses and supplies	0.700	⬥	⬥	⬥	⬥	45.60	⬥	⬥	⬥	⬥
123	Ship building	0.464	◆	⬥	⬥	◆	29.29	◆	◆	⬥	⬥
124	Railway equipment	0.768	◆	⬥	⬥	◆	52.74	◆	◆	⬥	⬥
125	Motor vehicle	0.583	◆	⬥	⬥	◆	38.12	◆	◆	⬥	⬥
126	Motorcycle, bicycle and other carriages	0.623	◆	⬥	⬥	◆	41.85	◆	◆	⬥	⬥
127	Repairing of Motor Vehicle	0.466	◆	⬥	⬥	◆	29.95	◆	◆	⬥	⬥
128	Aircraft	0.469	◆	⬥	⬥	◆	34.46	◆	◆	⬥	⬥
129	Scientific equipments	0.562	◆	⬥	⬥	◆	35.23	◆	◆	⬥	⬥
130	Photographic and optical goods	0.410	◆	⬥	⬥	◆	27.20	◆	◆	⬥	⬥
131	Watches and Clocks	0.380	◆	⬥	⬥	◆	24.46	◆	◆	⬥	⬥
132	Jewelry and related articles	0.345	◆	⬥	⬥	◆	22.47	◆	◆	⬥	⬥
133	Recreational and Athletic Equipment	0.472	◆	⬥	⬥	◆	30.71	◆	◆	⬥	⬥
134	Other manufacturing goods	0.620	◆	⬥	⬥	◆	38.10	◆	◆	⬥	⬥
135	Electricity	4.386	◆	⬥	⬥	◆	288.41	◆	◆	⬥	⬥
136	Pipe line	0.437	⬥	◆	⬥	◆	30.26	⬥	◆	⬥	◆
137	Water supply system	0.686	⬥	◆	⬥	◆	41.45	◆	◆	⬥	⬥
138	Residential building construction	0.699	⬥	◆	⬥	◆	64.17	⬥	◆	⬥	◆
139	Non-residential building construction	0.673	⬥	◆	⬥	◆	66.06	⬥	◆	⬥	◆
140	Public works for agriculture and forestry	0.664	⬥	◆	⬥	◆	65.50	⬥	◆	⬥	◆
141	Non-agricultural public works	0.713	◆	⬥	⬥	◆	66.31	◆	◆	⬥	⬥
142	Construction of electric Plant	0.641	◆	⬥	⬥	◆	54.44	◆	◆	⬥	⬥

Table 1 (*continued*)

		Energy intensity (TJ/million Baht)					GHG emission factors (ton $CO_{2\ equiv}$/million Baht)				
		1998	1995	1998	2001	2006	1998	1995	1998	2001	2006
143	Construction of communication facilities	0.614	◆	◆	◆	◆	46.58	◆	◆	◆	◆
144	Other constructions	0.523	◆	◆	◆	◆	52.46	◆	◆	◆	◆
145	Wholesale trade	0.184	◆	◆	◆	◆	11.31	◆	◆	◆	◆
146	Retail trade	0.204	◆	◆	◆	◆	11.63	◆	◆	◆	◆
147	Restaurant and drinking place	0.507	◆	◆	◆	◆	26.28	◆	◆	◆	◆
148	Hotel and lodging place	0.948	◆	◆	◆	◆	50.57	◆	◆	◆	◆
149	Railways	0.831	◆	◆	◆	◆	58.18	◆	◆	◆	◆
150	Route and non-route of road passenger trans.	1.336	◆	◆	◆	◆	93.56	◆	◆	◆	◆
151	Road freight transport	1.656	◆	◆	◆	◆	118.05	◆	◆	◆	◆
152	Land transport supporting services	0.174	◆	◆	◆	◆	10.57	◆	◆	◆	◆
153	Ocean transport	2.631	◆	◆	◆	◆	197.95	◆	◆	◆	◆
154	Coastal and inland water transport	1.094	◆	◆	◆	◆	80.06	◆	◆	◆	◆
155	Water transport services	0.215	◆	◆	◆	◆	13.50	◆	◆	◆	◆
156	Air transports	1.287	◆	◆	◆	◆	89.03	◆	◆	◆	◆
157	Other services	0.420	◆	◆	◆	◆	26.84	◆	◆	◆	◆
158	Silo and warehouse	0.761	◆	◆	◆	◆	41.41	◆	◆	◆	◆
159	Post and telecommunication	0.138	◆	◆	◆	◆	8.46	◆	◆	◆	◆
160	Banking services	0.163	◆	◆	◆	◆	9.73	◆	◆	◆	◆
161	Life insurnce service	0.120	◆	◆	◆	◆	7.36	◆	◆	◆	◆
162	Other insurance service	0.142	◆	◆	◆	◆	8.63	◆	◆	◆	◆
163	Real-estate	0.102	◆	◆	◆	◆	5.86	◆	◆	◆	◆

164	Business service	0.387	◆	◆	◆	◆	23.58	◆	◆	◆	◆
165	Public administration	–	–	–	–	–	–	–	–	–	–
166	Sanitary and similar services	0.540	◆	◆	◆	◆	38.19	◆	◆	◆	σ
167	Education	0.197	◆	◆	◆	◆	11.07	◆	◆	◆	◆
168	Research	0.567	◆	◆	◆	◆	37.64	◆	◆	◆	◆
169	Hospital	0.414	◆	◆	◆	◆	25.26	◆	◆	◆	◆
170	Business and labor associations	0.411	◆	◆	◆	◆	25.33	◆	◆	◆	◆
171	Other community services	0.339	◆	◆	◆	◆	21.59	◆	◆	◆	◆
172	Motion picture production	0.909	◆	◆	◆	◆	66.74	◆	◆	◆	◆
173	Movie theater	0.935	◆	◆	◆	◆	68.07	◆	◆	◆	◆
174	Radio, television and related services	0.335	◆	◆	◆	◆	19.03	◆	◆	◆	◆
175	Library and museum	0.211	◆	◆	◆	◆	12.78	◆	◆	◆	◆
176	Amusement and recreation	0.287	◆	◆	◆	◆	14.93	◆	◆	◆	◆
177	Repair, not elsewhere classified	0.491	◆	◆	◆	◆	30.15	◆	◆	◆	◆
178	Personal services	0.267	◆	◆	◆	◆	16.92	◆	◆	◆	◆
180	Unclassified	0.511	◆	◆	◆	◆	33.54	◆	◆	◆	◆

Note: The size of diamond bullets presents the comparisons of final consumptions' energy intensities or GHG emission factors in 1995, 1998, 2001, and 2006, i.e. ◆: Lowest value; ◆: Low value; ◆: Higher value; ◆: Highest value.

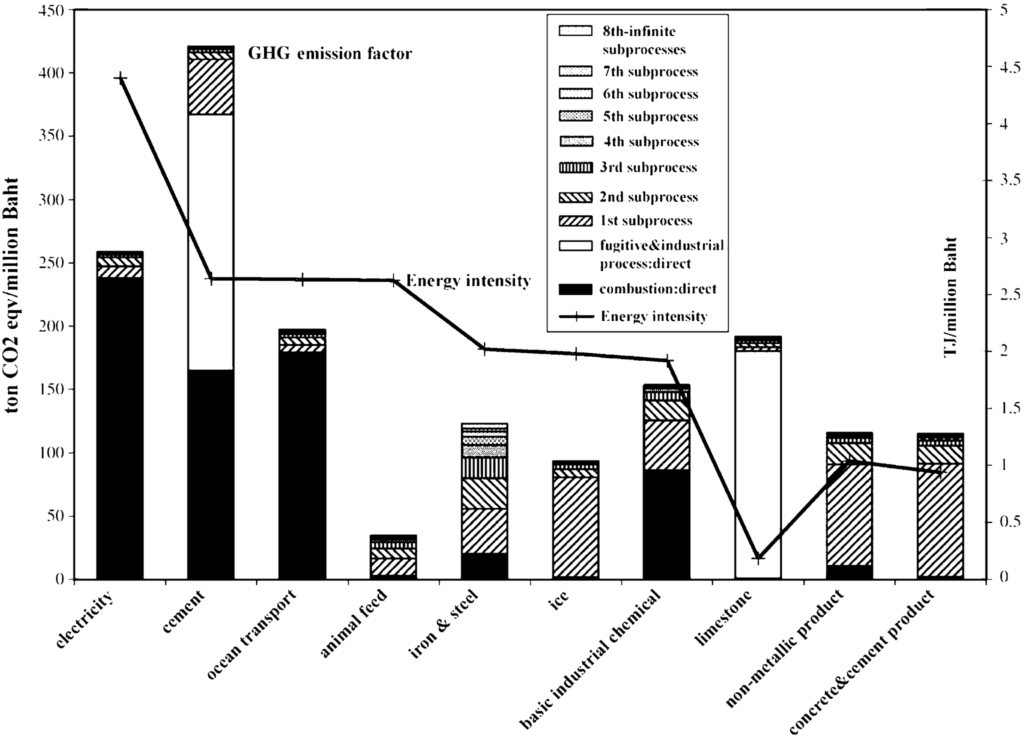


Fig. 2. GHG emission factors by bouundary layers.

the minihydro case are lower than any renewable technologies, while the PV case is the highest. Though the cost and energy intensity of the biomass case is higher than that of the minihydro case, the GHG emission factor of the biomass case is the lowest of all technologies. The lower emission factor of biomass electricity is due to the assumption of a closed-carbon cycle of biomass combustion.

The GHG emission factor in the minihydro case is 42.25 g $CO_{2\,\text{equiv}}$/kWh where about 44% is embedded in concrete dams, 28% is embedded in hydraulic equipment, 16.5% is embedded in electro-mechanical equipment, 8.4% is embedded in engineering fees and administration, and the remaining 3.4% is in steel pipe and transmission lines.

The emission factor of the biomass case is 26.77 g $CO_{2\,\text{equiv}}$/kWh. The highest source of emissions comes from the production chain for mechanical equipment of 46.6%, followed by the production chain for rice husk of 35.9 and 10.3% emitted from electrical equipment.

PV electricity is distinctive for being the highest GHG emitter and having the highest energy intensity. Since PV electricity is a non-mature technology and only in the demonstration stage in Thailand, the life cycle cost is as high as 32.7 Baht/kWh, whereas the average electricity price in 1995 was only 2.67 Baht/kWh. Major parts of PV system are imported. Although local production is assumed, the contribution of indirect imports of the electrical industrial machinery sector is very high. In IOA, the major portion is contributed in embedded emissions by materials from the electrical industrial machinery

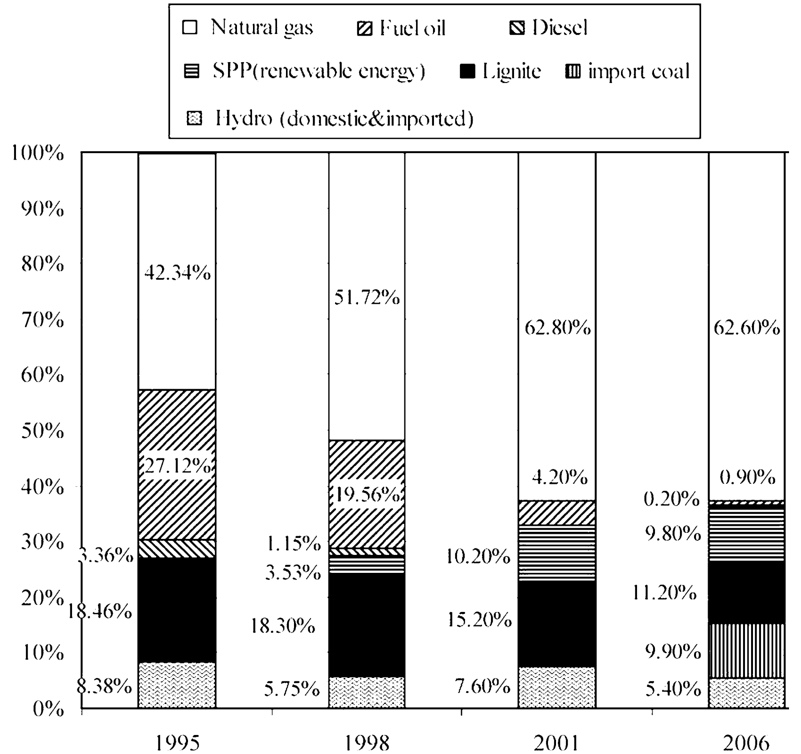


Fig. 3. Fuel mix in the electricity sector.

sector, i.e. solar arrays, battery banks, etc. accounting for about 95% of the emission factor.

3.3. Boundary consideration in subprocess chain order

Direct energy content contributes most of the energy content in fossil-fired technologies. Direct GHG contents from combustion activity are responsible for most of the life-cycle emissions in fossil technologies. They are about 95.35% in the GTCC case and 94.10% in fuel oil. Indirect emission responsible for only 4.65% and 2.87% embedded in the second subprocess of the GTCC case. Indirect emission is 5.90% and 52.46% of indirect emissions embedded in the first subprocess of fuel oil.

There are only indirect emissions in renewable energy technologies. Accounting for emissions up to the first subprocess causes truncation errors of 89.25% in the minihydro case, 85.63% in the biomass case, and 96.05% in the PV case. However, accounting up to the sixth subprocess can reduces truncation errors to 5.53% in the minihydro case, 6.99% in the biomass case, and 9.56% in the PV case.

Consideration of emission factors or energy intensity, only on the combustion stage yields an error in emission factors of fossil technologies, but truncates all contents in renewable technologies. An extension for one subprocess yields higher accuracy in the

Table 2
Comparison of direct and indirect GHG emissions and energy intensities of different electricity generation technologies

Input requirements from sector		Emission factors (g $CO_{2\,equiv}$/kWh)					Energy intensities (MJ/kWh)				
		GTCC	Fuel oil	Minihydro	Biomass	PV	GTCC	Fuel oil	Minihydro	Biomass	PV
Indirect		22.896	46.557	42.253	26.769	842.058	0.336	0.398	0.571	0.794	13.765
039	Limestone	—	20.637	—	—	0.185	0.020	—	—	—	—
049	Rice milling	—	—	—	9.612	0.672	—	—	0.529	—	—
064	Soft drink	—	—	—	0.453	0.423	—	—	0.007	—	—
084	Basic industrial chemicals	0.351	—	—	1.007	1.920	—	—	0.013	—	—
093	Petroleum refineries	—	18.515	—	—	0.360	0.269	—	—	—	—
106	Secondary steel products	—	—	0.745	—	1.102	—	0.013	—	—	—
112	Engines and turbines	1.699	1.528	—	—	0.726	0.023	—	—	—	—
114	Woodandmetal work m/c	—	—	—	0.153	0.481	—	—	0.002	—	—
115	Special industrial m/c	0.131	3.047	11.809	12.463	0.641	0.047	0.181	0.191	—	—
117	Electrical industrial m/c	0.040	1.069	6.968	2.755	0.417	0.018	0.115	0.046	13.242	799.606
120	Insulated wire and cable	—	—	0.690	—	0.548	—	0.011	—	—	—
136	Pipe line	18.818	—	—	—	0.438	—	—	—	—	—
137	Water supply system	0.700	—	—	0.211	0.687	—	—	0.004	—	—
139	Non-residential building construction	—	—	—	—	0.673	—	—	—	0.232	22.379
140	Public works agricultural and forestry	–	—	18.493	—	0.665	—	0.191	—	—	—
141	Non-agricultural public works	0.211	0.598	—	—	0.714	0.007	—	—	—	—
142	Construction of electric plant	0.747	0.880	—	0.040	0.642	0.011	—	0.000	0.123	10.203
164	Business services	0.200	0.283	3.549	0.076	0.387	0.005	0.061	0.001	0.169	9.870
Direct		420.100	743.200	—	—	—	7.526	9.703	—	—	—
Indirect domestic		19.312	30.236	27.642	14.643	290.321					
Indirect import		3.583	16.321	14.611	12.127	551.737					
1st indirect domestic		13.569	3.978	15.630	4.011	151.130					
2nd indirect domestic		3.086	1.166	5.235	4.963	66.093					
3rd indirect domestic		0.932	0.418	1.439	1.169	25.385					
4th to infinite domestic		1.726	24.674	5.338	4.499	47.714					
Total		442.996	789.757	42.253	26.769	842.058	7.862	10.101	0.571	0.794	13.765
Life cycle cost (Baht/kWh)		0.718	0.931	1.034	1.233	32.699					

fossil technologies, but large truncation still exists in renewable technologies. The result of domestic accounting of the minihydro case up to the second subprocess in this study (20.86 g $CO_{2\,equiv}$/kWh) is close to the inventory analysis of Gagnon [28] and Van de Vate [29] for 20 g $CO_{2\,equiv}$/kWh. However, the minihydro case in this study does not account for methane emissions from the decay of biomass as Gagnon and Van de Vate considered, since this amount is not large in the run-off-river hydro plant.

The results of total emission factors for the PV case in this study are distinctively different from other research that performed much more detailed analysis by PCA. Accounting up to infinite subprocess boundary, the GHG emission factor of the PV case is five to seven times higher than the result of Van de Vate [30] (100–300 g $CO_{2\,equiv}$/kWh) and the result of Voorspools [5] (110–160 g $CO_{2\,equiv}$/kWh). When accounting for the GHG emissions up to the second subprocess, consideration is comparable to the one derived by PCA (217.22 g $CO_{2\,equiv}$/kWh). However, the PV emission factors derived from the combined PCA and IOA in this study are slightly lower than the CO_2 emission factor of 1105.42 g CO2/kWh derived from IOA by Proops et al. [31] in UK. Emission factors of German PV that is derived by GEMIS software [32], an LCA method based on PCA, is approximated at about 100–110 g $CO_{2\,equiv}$/kWh. The higher emissions in Thai PV plants than those of PCA are because of the higher cost of PV electricity and higher order of boundary consideration. In addition, about 63% of the emission factor of PV electricity would be omitted if indirect imports were not considered. The emission factor for the Thai electricity mix in 2006 is 631.35 g $CO_{2\,equiv}$/kWh, and for Belgium by Voorspool et al. [5] is 340 g $CO_{2\,equiv}$/kWh due to different fuel mixes that would yield much higher indirect emission factors in all other sectors. The geographic condition is also a factor of different GHG emission factors for PV in different countries.

This article also extends the energy chain boundaries to infinite processes with the advantage of IOA. If PCA could be done similarly in the Thai economy, the emission factors of each electricity production technology could be expected as far as the second level of subprocess chain boundary.

4. Conclusions and recommendations

The IOA study reveals the implications of the indirect as well as the direct energy related GHG emissions in the Thai economy. The energy intensities and total GHG emission factors in final consumptions found in this study could be further applied for comparative assessment in other energy projects in Thailand. Though the energy related GHG have to be derived from the amount of energy consumption, there is no proportionality between 'energy intensity' and 'greenhouse gases intensity'. There are two explanations: firstly, disparity of GHG emissions from combustion of different fuels, and secondly, GHGs could be emitted in some other activities rather than combustion of fuels. Delineation of most sectors into subprocess orders and activities reveals that we could not neglect indirect effects beyond the direct combustion in the conversion stage of any commodities' production.

The highest GHG intensive sector in the Thai economy is the cement sector having emissions from fossil fuel combustion and production processes. The electricity sector is the highest energy intensive sector and the second highest GHG intensity sector due to a large contribution of direct GHG emission from fossil-fuel combustion. The high emission

factor of the electricity sector indirectly induces high emission factors in most sectors, since electricity is the basic requirement for other sectors in the Thai economy.

The assessment of GHG emissions from the selected case studies reveals that input requirements in the operating stage directly affect the life-cycle GHG emission factors in terms of direct and indirect emissions and energy intensities. The high GHG emissions come from high direct combustion of fossil-fuel energy and high emissions embedded in the energy chains of these consumable goods, including methane emissions from the production of fossil energy, and emissions from some production processes such as lime production The contribution of indirect GHG emissions and energy content from the production of materials and services during implementation and maintenance is negligible in the fossil-based technologies, but it is significant in the renewable energy technologies. The boundary of the full energy chain analysis is significant, particularly for the renewable energy technologies whose direct emissions are absent. The trend of indirect emissions would be lower in the case of successful substitution of renewable energy technologies, which cause upstream interruption of emissions from the fossil-fuel chain within the economy, particularly recommended in the electricity sector. This article also copes with the embedded GHG emissions in imported commodities. The assumption that foreign technology contributes the same values of energy and GHG intensities as domestic ones may be underestimated if the imported commodities come from higher intensive industries than the local ones, and vice versa.

Once the global warming becomes an important issue, long-term policy making on a lower GHG emitting project should be done in terms of full-energy-chains analysis. All infinite subprocess chains should be taken into account, but the boundary layer of PCA in the Thai energy projects is very narrow due to limitation of data availability. At the higher subprocess order, it needs embedded energy and total GHG emission factors from IOA to evaluate the remaining energy and GHG emissions in extended boundary layers. However, to improve the accuracy of the full-energy-chain analysis, it needs to extend the boundary of PCA. It means that a large extension on field surveys on relevant industrial sectors is required. One level extension requires energy and emissions auditing on all production processes of all input requirements of the previous level.

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